GEOPHYSICAL SURVEYS OF THE MILFORD, UTAH, FORGE SITE: GRAVITY AND TEM

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ABSTRACT

Basement geometry of the Milford, Utah, Frontier Observatory for Research in Geothermal Energy (FORGE) study area has been better defined by augmenting legacy data with 417 new, high-precision gravity measurements using a dynamic grid layout and 34 transient electromagnetic (TEM) soundings in transects. The FORGE site is situated over Tertiary-Quaternary granitic intrusions and Precambrian gneiss that crop out in the Mineral Mountains. These same rock types are also found at 3 km depth in the Acord-1 well 10 km to the west of the site, near the center of Milford Valley. Modeling of the 30 mGal gravity low, caused by basin fill overlying the granite, was accomplished using a decreasing density contrast with increasing depth. This framework was based primarily on the Acord-1 and FORGE 58-32 wells, geophysical logs, laboratory measured physical properties, and local geologic information. Two-dimensional (2D) gravity models indicate that the deepest part of the basin, approximately 4.8 km in depth, is located on the west side of the valley, 12 km from the edge of the FORGE site boundary. Basin geometry from the 2D gravity modeling shows a steeply dipping interface on the east side of Milford Valley north of the FORGE site. Electrical resistivity models from the TEM data do not indicate any anomalous structure near the surface within the study area. A TEM transect through the FORGE site delineates the depth to the groundwater table which varies from 60 to 150 m. South of the FORGE site, another TEM transect crosses the Opal Mound fault (OMF), where a distinct resistivity contrast shows conductive material to the east of the fault that is interpreted to be primarily an effect of geothermal fluids that are prevented from flowing to the west by the fault. Electrical resistivity values along the Ranch Canyon transect are relatively high compared to those to the north. The sediment-basement interface below the FORGE site appears to be moderately dipping (about 25˚) to the west, which is consistent with interpretations of 2D and 3D seismic sections.

INTRODUCTION

Geophysical data collected during the 2017 field season have been used in a preliminary characterization of the Milford, Utah, Frontier Observatory for Research in Geothermal Energy (FORGE) site in southeastern Utah. A total of 34 new transient electromagnetic method (TEM) soundings and 417 gravity stations were added in Phase 2 of the FORGE project (Figures 1 and 2). TEM soundings are sensitive to electrical properties of the subsurface, which are manifested by attenuation of the magnetic field. TEM surveys can help delineate shallow (300–400 m) subsurface features if they have a notable resistivity contrast relative to adjacent material. The gravity field is sensitive to density distribution in the subsurface which can help us delineate structures such as faults or large buried objects underground. The aim of this geophysical work is to locate and identify subsurface structures that could impact the FORGE site operations as well as obtain a better understanding of the local geology.

TEM SURVEY AND METHODS

We conducted a TEM geophysical survey to better define subsurface structures and features near the FORGE site (Figure 2). TEM is an active-source method that measures the attenuation signal of induced magnetic fields corresponding to changes in the electrical properties in the subsurface. TEM measurements were made at 34 unique locations within the FORGE study area using an ABEM WalkTEM ground loop system fitted with a 40-x-40-m transmitter antenna as well as high- and low-frequency receiver antenna coils capable of simultaneous recording. Repeat measurements were carried out at specific locations to ensure data consistency and quality for the duration of the field survey period. The time spent at each station location was less than one hour with two to three measurements completed during that time as well as subsequent checking of the field data. All TEM stations yielded high-quality data with excellent signal-to-noise ratio except for one station that was deemed less useful due to very conductive surface conditions and, perhaps, cultural noise (utility lines, etc.) at the site location.

After initial data processing, one-dimensional (1D) inversion models for every station were created (Auken et al., 2015) and improved by screening data bands until data fit was satisfactory. Using 1D TEM models and a Digital Elevation Model (DEM),

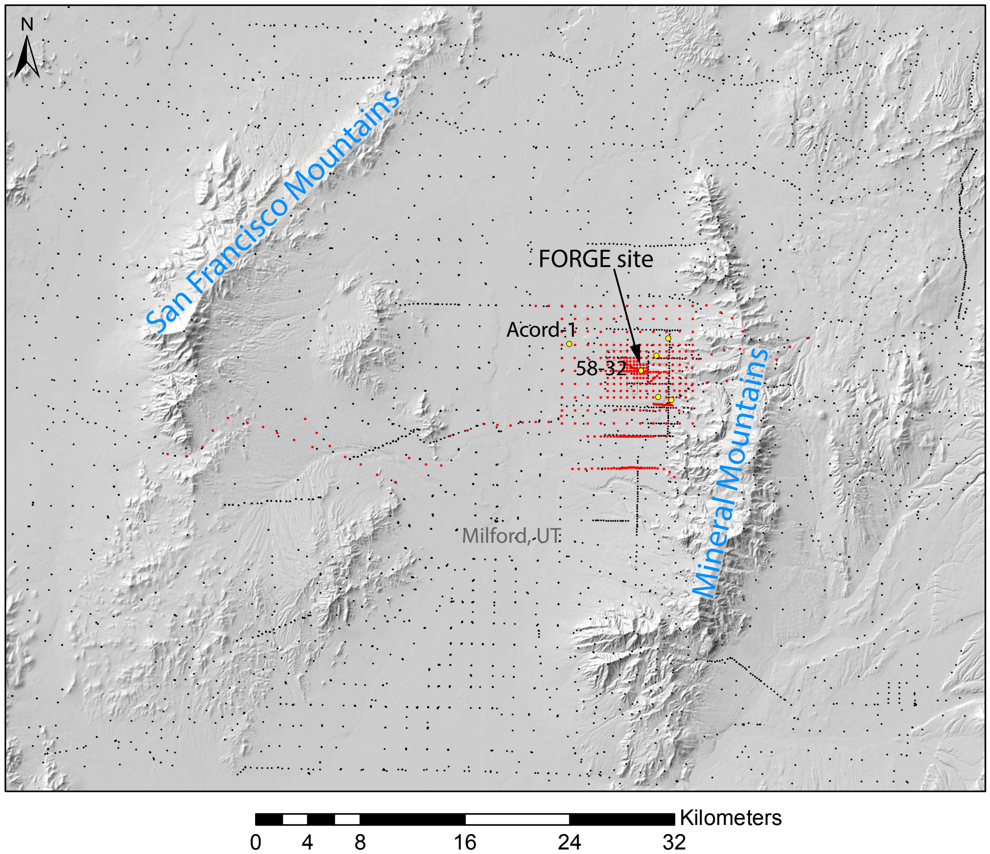

Figure 1. *Shaded elevation map of Milford Valley area showing coverage of new gravity stations (red dots), legacy gravity data (black dots), and control wells (yellow dots).*

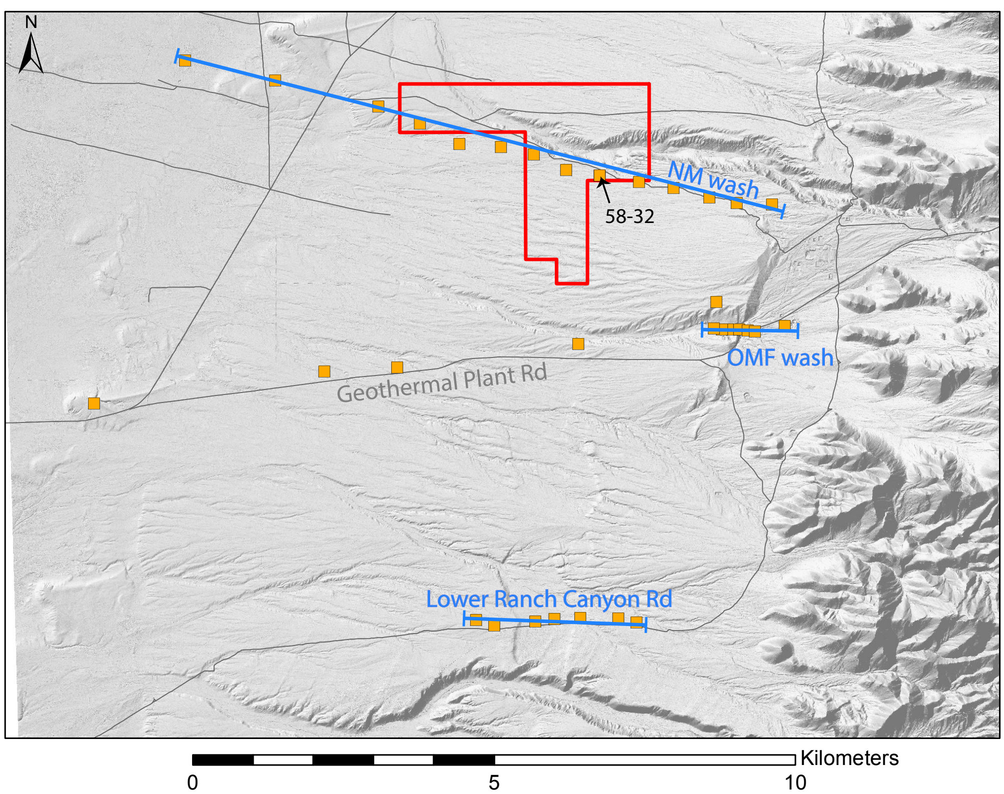

Figure 2. *Map of TEM station locations (orange squares) and transects (blue lines) for the FORGE study area (outlined in red). The transects Negro Mag (NM) wash, Opal Mound fault (OMF) wash, and Lower Ranch Canyon Rd are shown.*

pseudo two-dimensional (2D) sections of resistivity were created to aid interpretations. The pseudo 2D sections display the 1D resistivity and are constrained using the Depth of Investigation (DOI) parameter (see Spies, 1989; Christiansen and Auken, 2012). DOI is unique for each station, relies on the physical properties of subsurface material, and indicates the maximum depth of resolution with respect to modeling. When extending modeling deeper than the DOI, confidence in the resulting 1D and 2D models will subsequently decrease with increasing depth.

TEM RESULTS

The DOI values for the study area range from approximately 100 m to 400 m with an average of 300 m. The pseudo 2D sections (Figures 3 to 5) show the 1D model results from the TEM transects shown in Figure 2, as well as interpolated electrical resistivity values between the 1D models (to be used only as a visual aid). Background resistivity values within the study area range from 10 to 1000 Ohm·m, which are inferred to be the signature of fine, clay-rich valley fill (low resistivity, approximately 10 to 30 Ohm·m) as well as coarser fill on the alluvial fans consisting of sand and gravel that are closer to their sources (high resistivity, 100–1000 Ohm·m).

Resistivity model interpretations provide insight to the subsurface conditions at three areas around the FORGE site (Figure 2). Figure 3 shows the NM wash transect, which is the longest of the sections, starting in the valley and terminating near the north end of the Opal Mound fault (OMF). No significant structures were detected by TEM data on this transect. The groundwater table is well defined at the boundary where resistivity decreases from 100 to 10 Ohm·m (green-yellow transition). On the eastern end of the transect, low resistivities are detected near the surface, which are interpreted to be shallow hydrothermal outflow from Roosevelt Hot Springs (RHS).

Figure 4 shows the OMF wash transect, which crosses the OMF from west to east between stations FM19 and FM20. There is a resistivity jump between these stations from 40–50 Ohm·m to 10–20 Ohm·m. The lower resistivity values are likely due to conductive pore fluids consistent with the RHS hydrothermal system (Archie, 1942). The OMF appears to act as a flow barrier, keeping low-resistivity geothermal fluids from flowing westward. FM22, the farthest east sounding, detects shallow, higher-resistivity layers of more than 100 Ohm·m. These layers are interpreted as coarse sand and gravel near their source in the Mineral Mountains.

Figure 5 shows the Lower Ranch Canyon Road transect, where resistivity values are much higher than the northern transects. The resistivity models show no anomalous structures in the shallow subsurface and the groundwater table is detected between 1550 and 1600 m elevation above sea level (blue-green transition). The background resistivity ranges from 100 to 1000 Ohm·m in this area, which is attributed to its proximity to igneous source rocks of very high resistivity (1000 to 100,000 Ohm·m when in an unweathered state). Rapid burial of the eroded material could slow weathering and result in higher resistivity values. FM09 displays a resistive body at approximately 200–250 m depth which we believe is a result of noisy data and it is not interpreted to be real.

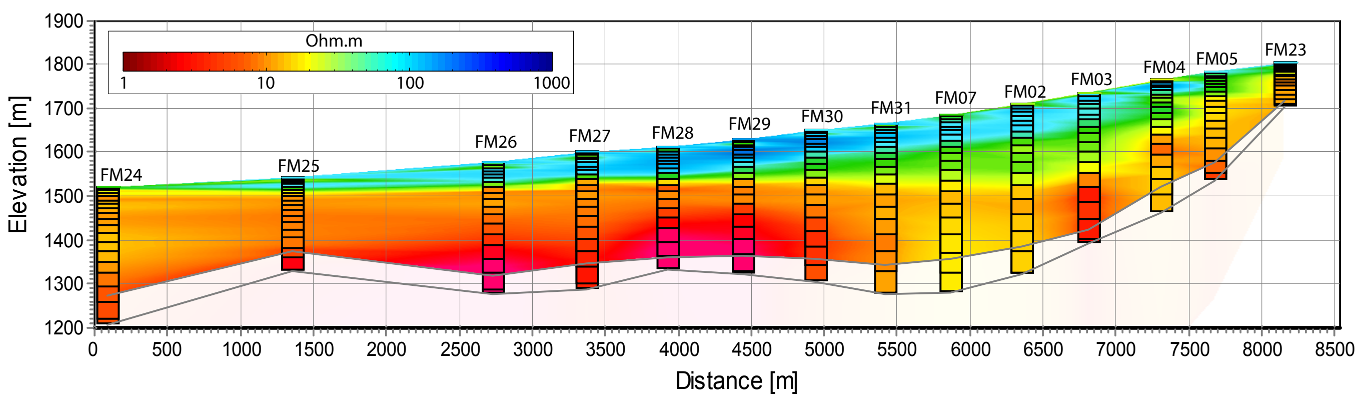

Figure 3. *Resistivity models shown as a pseudo-section for the NM wash transect. TEM station names are indicated; FORGE well 58-32 co-located with station FM07 and the gray lines show the DOI parameter. The groundwater table corresponds to the top of the 20 Ohm·m layer (yellow).*

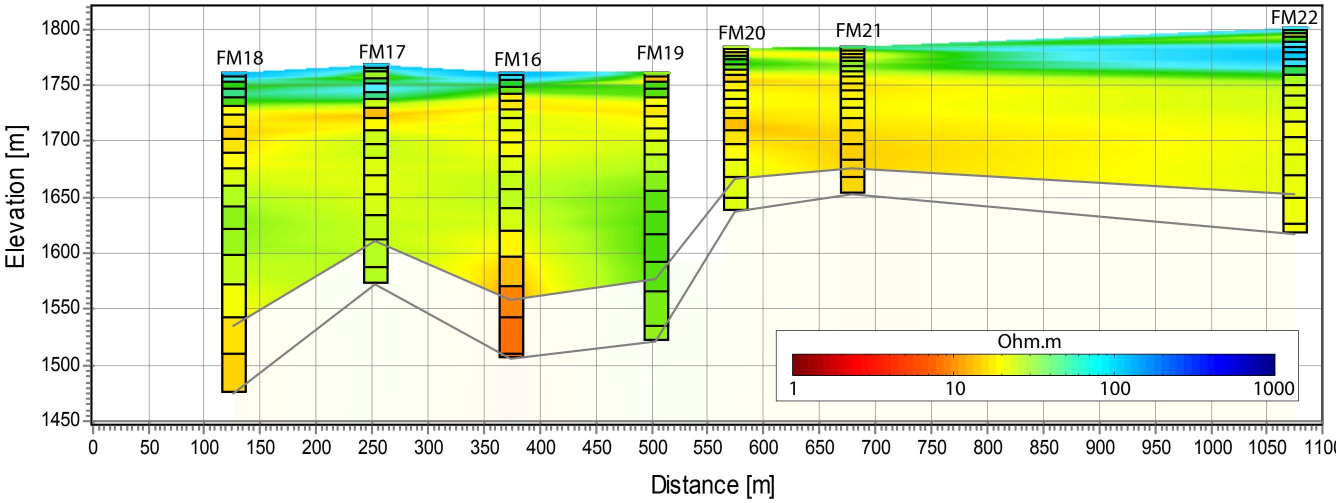

Figure 4. *Resistivity models shown as a pseudo-section for the OMF wash transect. TEM station names are indicated and gray lines show the DOI parameter. Horizontal resistivity contrasts are captured on opposite sides of the OMF; on the east side (FM20–FM22) the values are more conductive due to hydrothermal pore waters compared to the west side (FM16–FM19) where hydrothermal fluids are absent. This suggests the OMF acts as a barrier to fluid flow.*

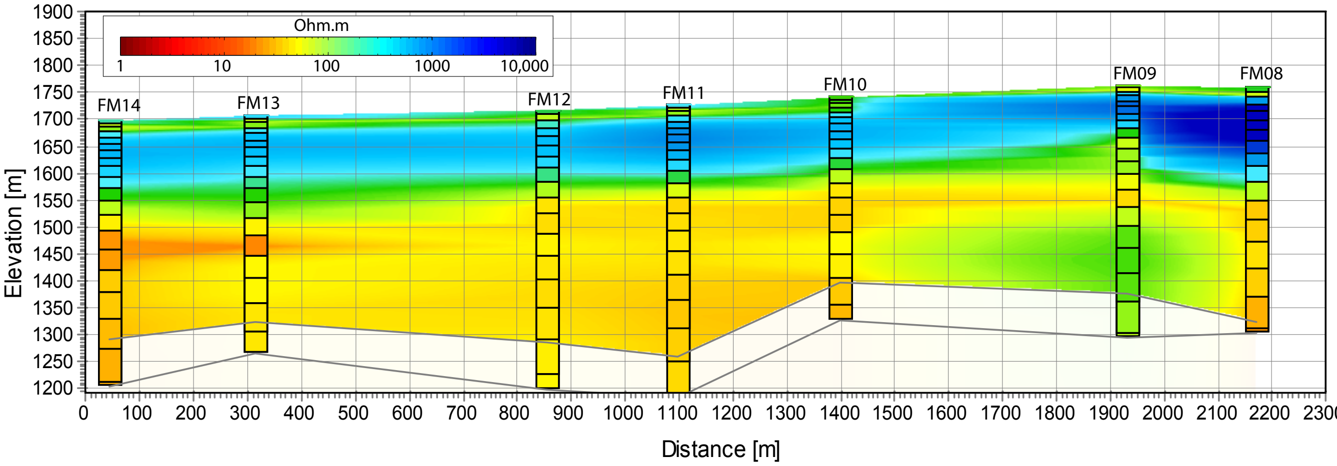

Figure 5. *Resistivity models shown as a pseudo-section for the Lower Ranch Canyon Road transect. TEM station names are indicated and gray lines show the DOI parameter. The groundwater table corresponds to the top of the 100 Ohm•m layer (green) observed between 1550 and 1600 m elevation.*

GRAVITY SURVEY AND METHODS

A total of 417 new gravity stations were combined with 3389 legacy gravity stations to achieve better coverage near the proposed drill sites and in the basin (Figure 1). A varied-offset survey grid was utilized for gravity measurements made near the proposed drill sites. Station spacing started at 250 m near the FORGE area and then stepped to 500 m and 1 km. This spacing keeps the data density high for better resolution of 3D gravity inversion models closer to the FORGE area while still providing good resolution farther from the site. Legacy gravity data is sourced from Pan American Center for Earth and Environmental Studies (PACES). Field measurements were made using two Scintrex CG-5 gravimeters following the methods of Gettings et al. (2008); we used a 10-minute time series and reoccupation of local bases only. Elevation control on most of the stations is better than 0.1 m, which was achieved through post-processing of high-precision GPS data, resulting in a gravity accuracy of better than 0.03 mGal. The Complete Bouguer Gravity Anomaly (CBGA) was computed using a reduction density of 2.67 g/cm^3 and the formulas outlined by Hinze et al. (2005). Horizontal gravity gradient fields were computed, followed by 2D gravity models of five transects using the Semi-Automated Marquardt Inversion code (SAKI; Webring, 1985). Density-depth relationships for basin-fill and rock densities were taken from existing well logs and laboratory-measured physical rock properties of field samples and drill cuttings from the FORGE well 58-32 (Gwynn et al., 2019). Initial models and densities were calibrated using wells containing both density logs and basement depth values. Calibrated density values were then used in subsequent 2D models. The basement depth values were taken from 2D gravity and 1D Magnetotelluric (MT) models (Hardwick et al., 2015) and well data, and then used to develop a depth-to-basement map.

RESULTS

The CBGA (Figures 6 and 7) shows that the dominant basin signal trends north-south. This prominent, north-trending, -30-mGal gravity low is approximately 16 km wide and is bounded by gravity highs to the east and west. 2D gravity models (Figures 8–12), transects of which are shown on Figure 6, were chosen based on the high quantity of data along the line (providing higher confidence in the gravity field values). The models use the x-coordinate of the FORGE 58-32 well as the reference in distance along each transect.

Looking at the 2D models from north to south, the steepest side of the Milford basin shifts from the east to the west side (compare Figures 8 and 10), which is suggested by the shaded CBGA map (Figure 7). Tighter contouring indicates relatively larger changes in the gravity field, which are interpreted as more steeply dipping interfaces between the less dense basin fill and higher density bedrock. There does not appear to be any significant basement structures based on the results of widely spaced 2D gravity modeling near the FORGE area. However, a subtle feature to the west of the FORGE area was observed in the horizontal gravity gradient (Figure 13), indicating slight changes in the gravity field (i.e., subsurface density changes or basement topography). This feature may be the gravity signature of the paleo valley in the surface of the granite delineated by the 3D seismic reflection survey interpretations (Miller and others, 2019). Future 3D gravity modeling and integration with the 3D seismic reflection interpretation may be able to better map this feature. Figure 14 shows the composite model of the Milford basin developed using gravity survey data, 1D MT models, and well data.

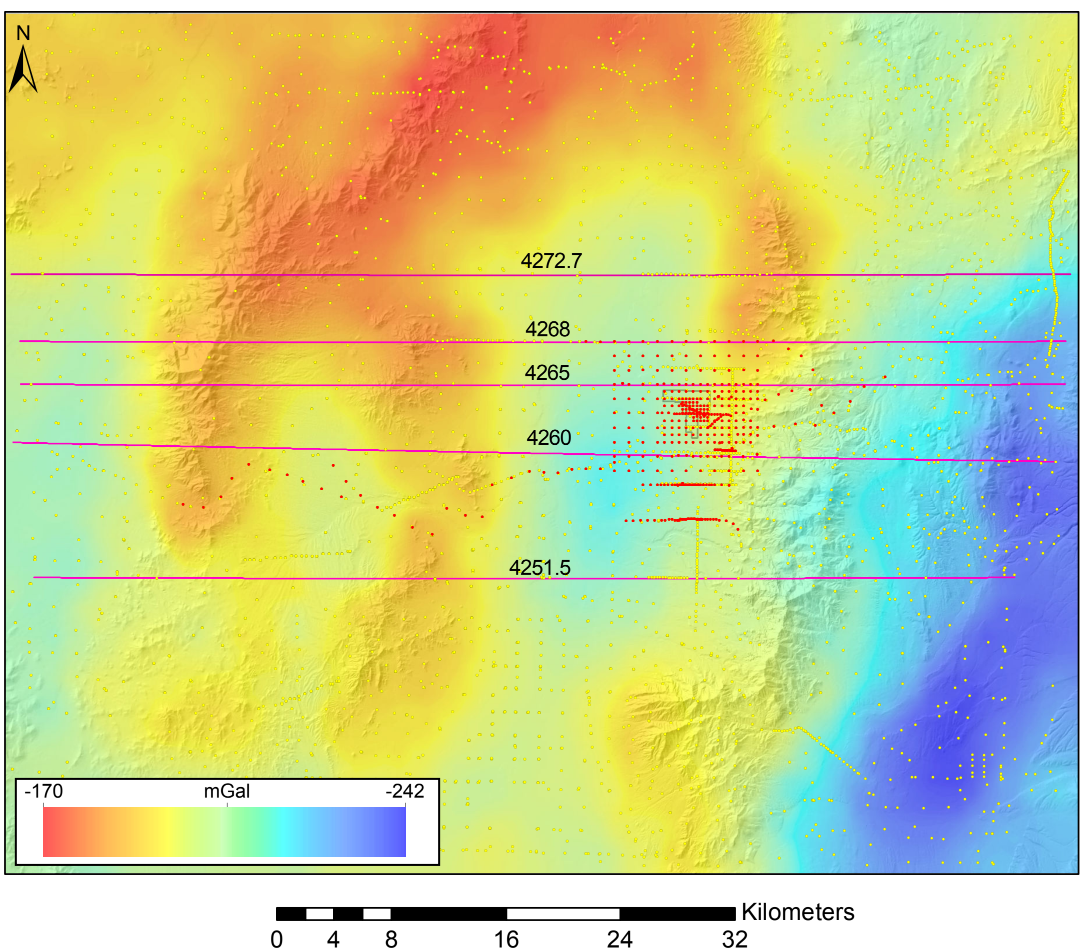

Figure 6. *The CBGA for the Milford, Utah, FORGE site overlain on shaded topography. New gravity stations are shown as red dots and the legacy gravity data area is shown as yellow-filled dots. Magenta lines are 2D model transects (see Figures 8 through 12) labeled by UTM northing in units of km.*

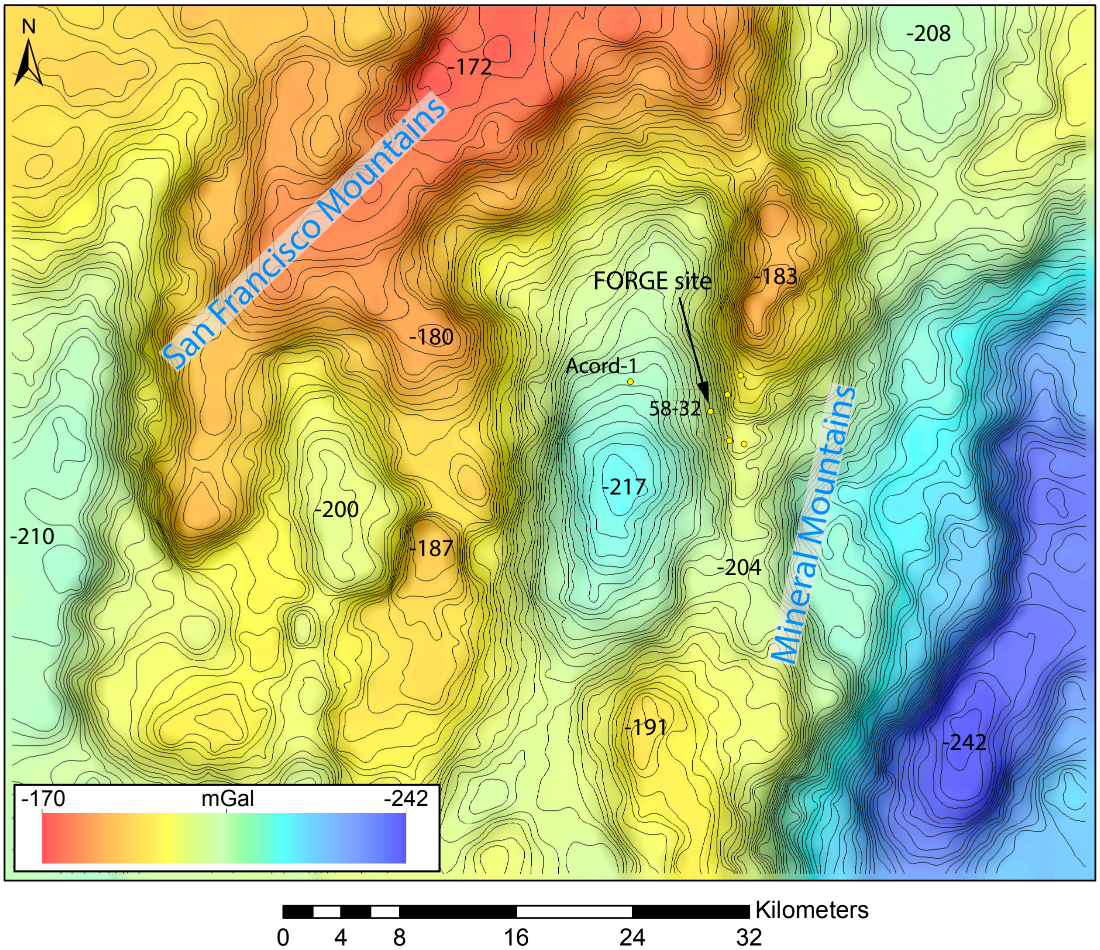

Figure 7. *Map of CBGA with shading generated from the horizontal gravity gradient. Anomaly values are in units of mGals and contours are in 1 mGal increments.*

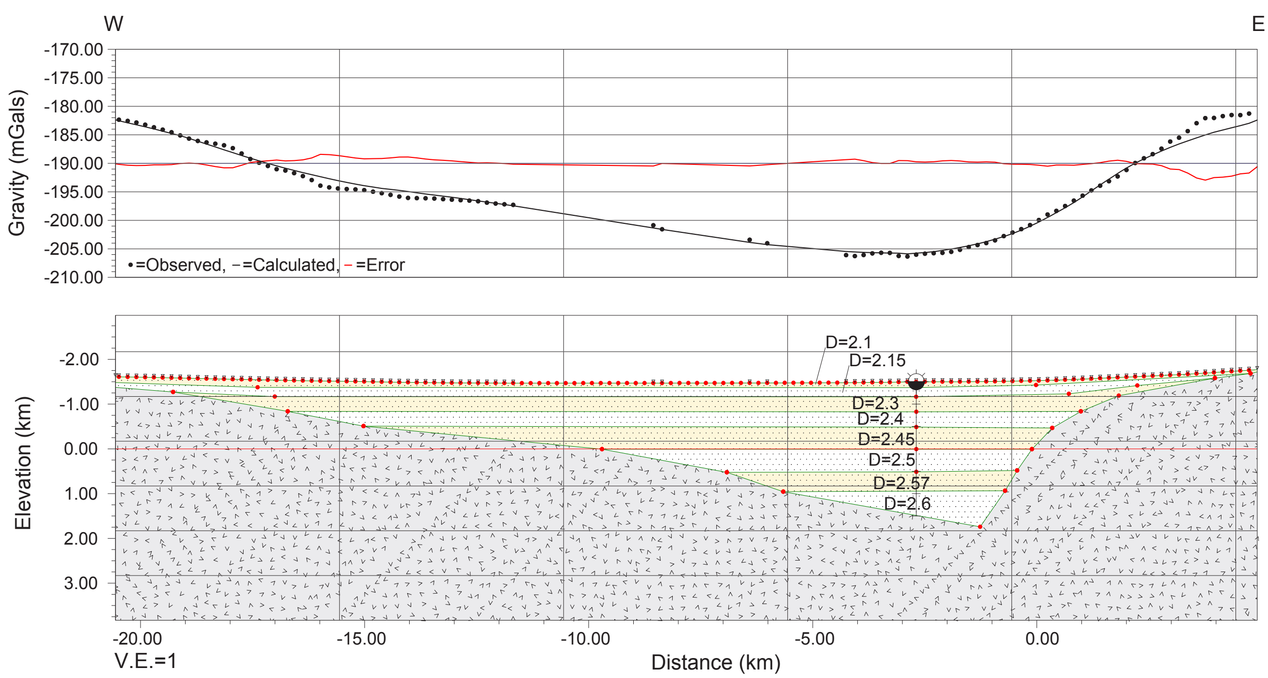

Figure 8. *2D model transect 4272.7 (see Figure 6). The model shows asymmetric basin geometry, with a gentle slope on the west side and steep slope on the east side. The maximum depth of the basin model from ground surface is 3241 m at the eastern end. Density values of the layers are given in g/cm*^{3}.

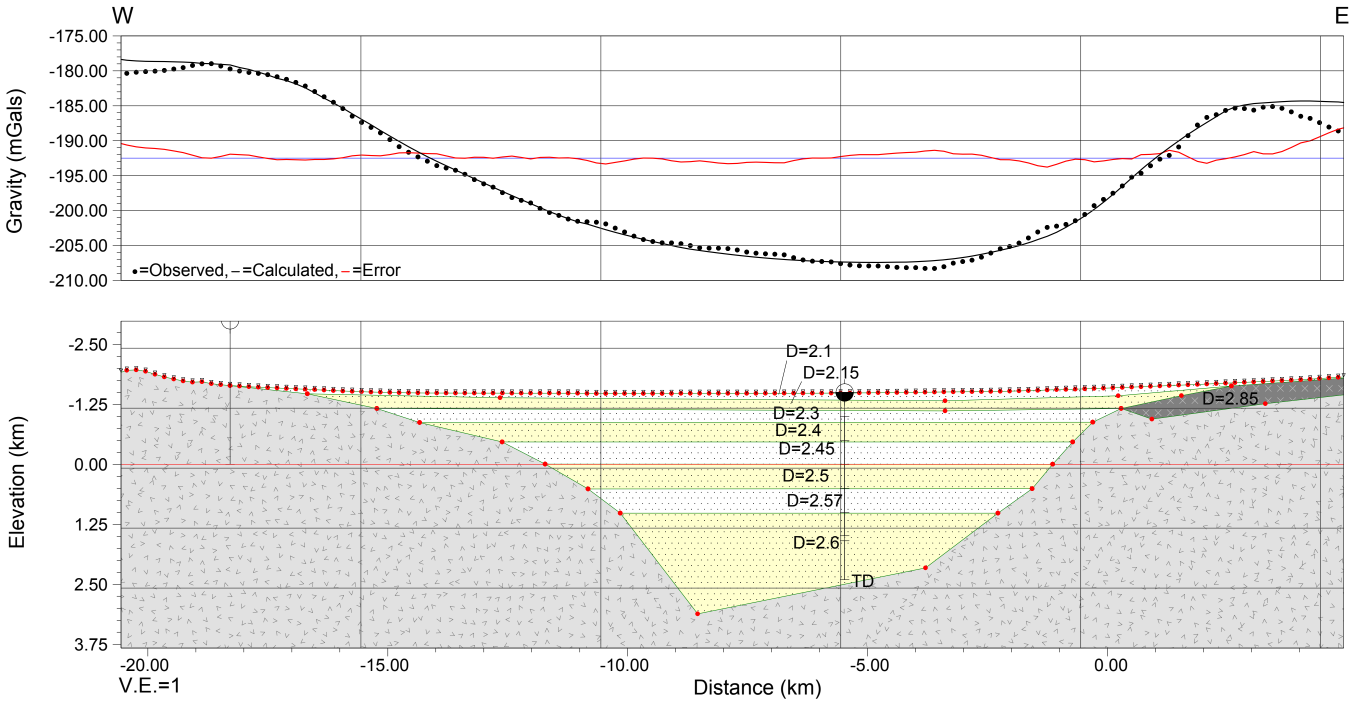

Figure 9. *2D model transect 4268 (see Figure 6). The model shows a somewhat asymmetric basin geometry, with a steep, convex-shaped slope on the west side and moderately steep slope on the east side. The maximum depth of the basin model from ground surface is 4596 m located more central in the basin. Density values of the layers are given in g/cm*^{3}.

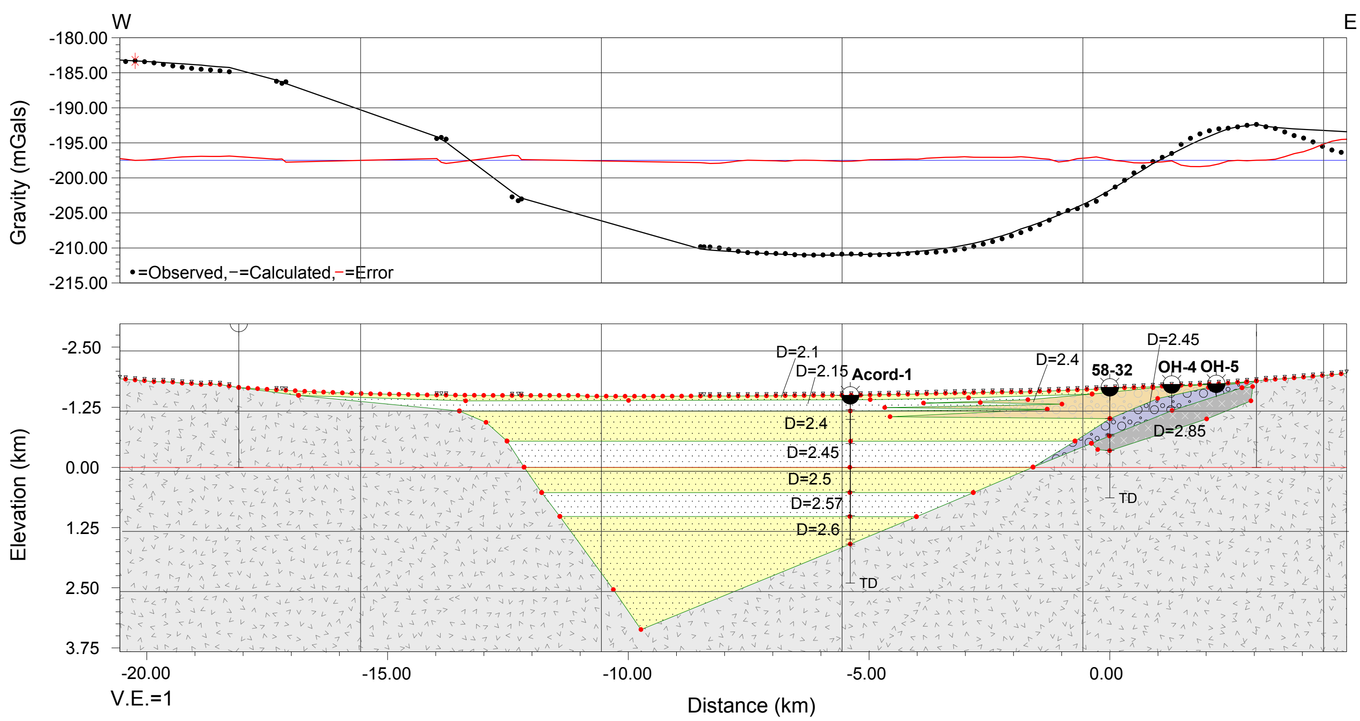

Figure 10. *2D model of transect 4265 (see Figure 6). The model shows an asymmetric basin geometry, with a steep slope on the west side and a moderate slope on the east side. The maximum depth of the basin model from ground surface is 4742 m located west of the center of the basin. Wells Acord-1, 58-32, OH-4, and OH-5 were used as control points for depth and density. Density values of the layers are given in g/cm*^{3}.

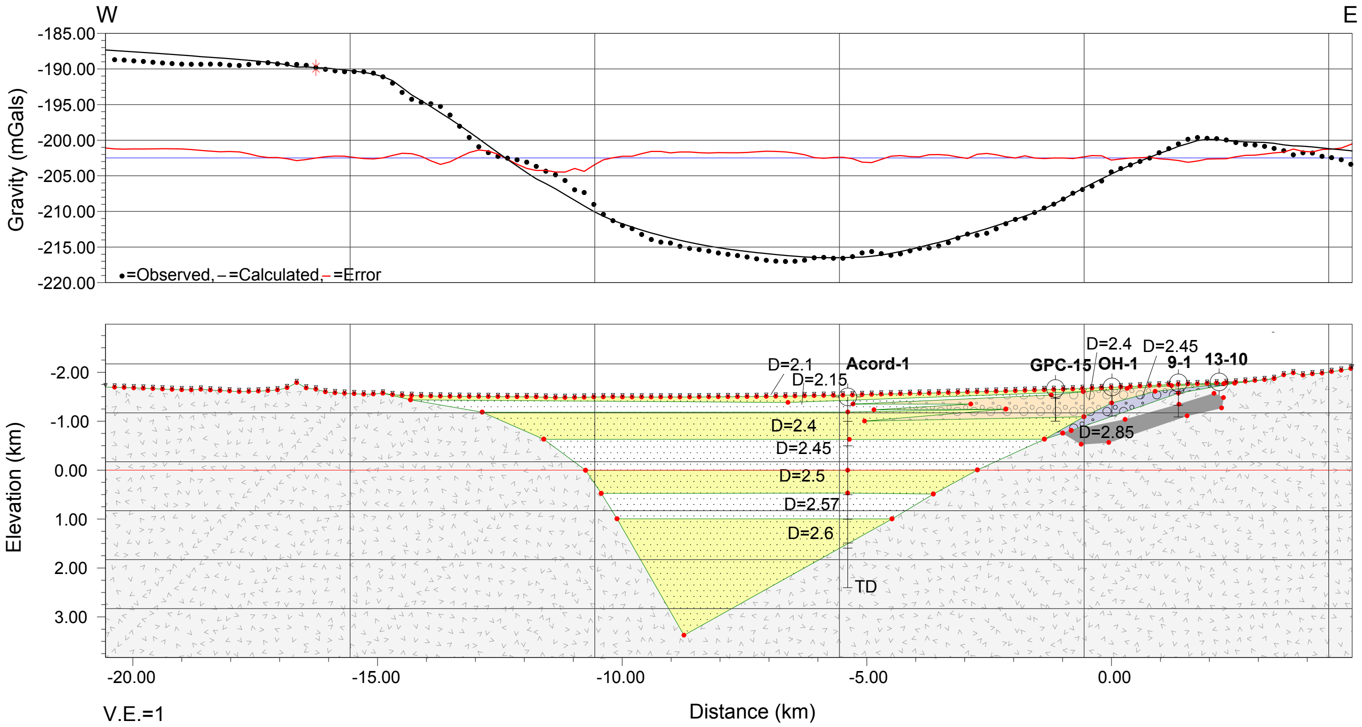

Figure 11. *2D model of transect 4260 (see Figure 6). The model shows an asymmetric basin geometry, with a steep slope on the west side and a moderate slope on the east side. The maximum depth of the basin model from ground surface is 4872 m located west of the center of the basin. Wells 9-1, 13-10, Acord-1, GPC-15, and OH-1 were used as control points for depth and density. Density values of the layers are given in g/cm³.*

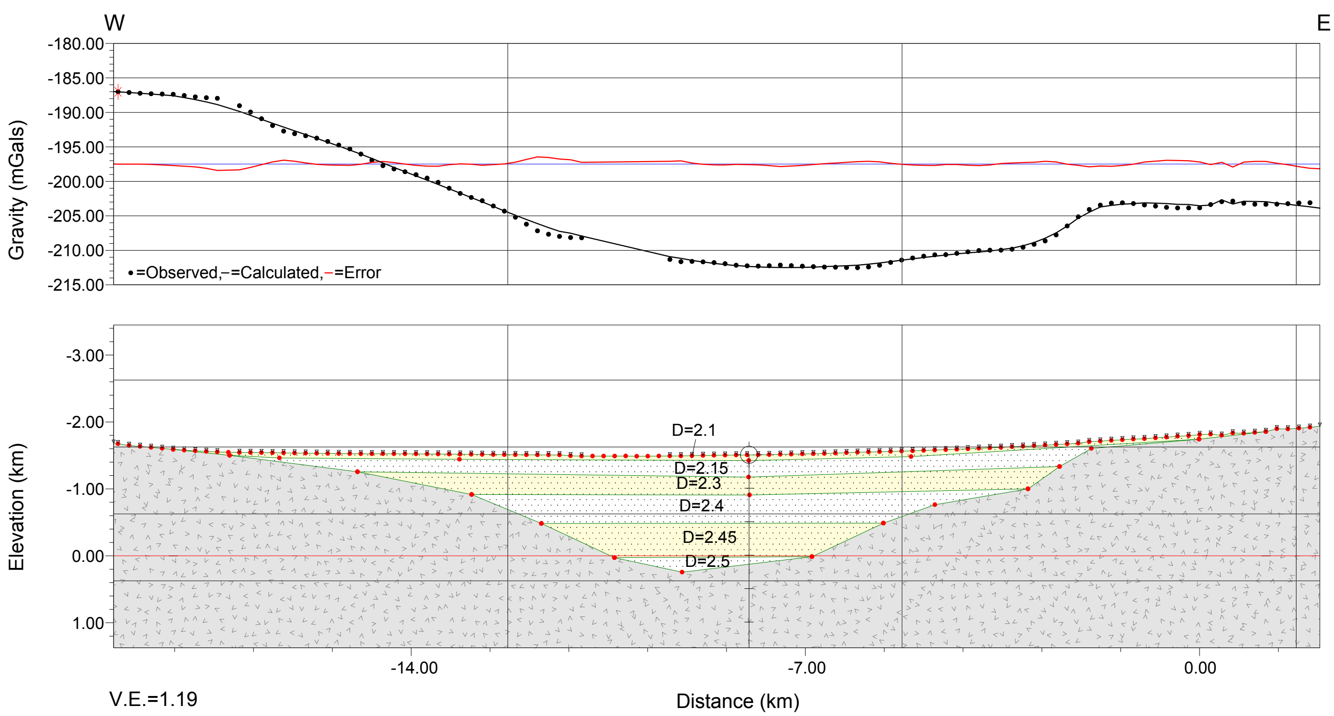

Figure 12. *2D model of transect 4251.5 (see Figure 6). The model shows near symmetric basin geometry, with gradual slopes on the west and east sides. The maximum depth of the basin model from ground surface is 1735 m located near the center of the basin. Density values of the layers are given in g/cm³.*

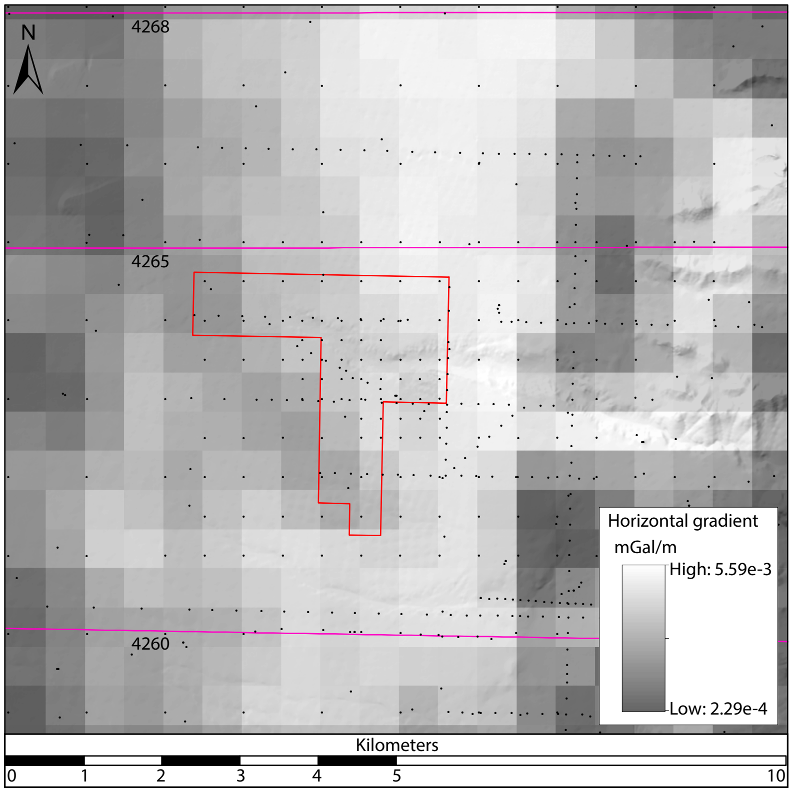

Figure 13. *Map of the local horizontal gravity gradient. The FORGE site outline is red, the 2D gravity transects are in magenta, and the gravity stations are black dots. A feature in the gradient is observed trending NW-SE to the west of the FORGE site outline.*

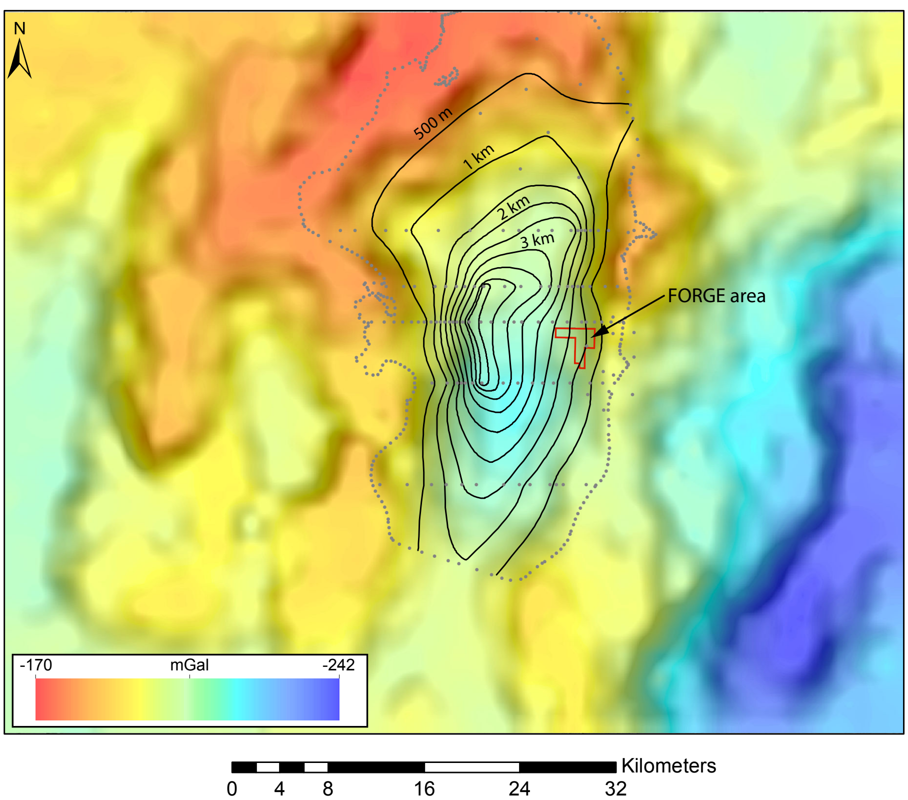

Figure 14. *Basement depth map for the Milford, Utah, FORGE site. The base map is colored by CBGA values with shading generated from the horizontal gravity gradient and overlain with contours of basement depth in Milford Valley. Contours are in 500 m increments and basement control points (gray dots) are from 2D gravity models, 1D MT models, and zero-depth picks on, or adjacent to, outcrop. The deepest part of the basin model is on the western side of the valley.*

QUANTIFICATION OF UNCERTAINTY

In gravity surveying, we consider all the following for sources of error/uncertainty: equipment precision, data processing errors, GPS precision, terrain corrections, and anomaly corrections. The Scintrex CG-5 autograv gravimeter has a measurement precision of 0.001 mGal and accuracy better than 0.005 mGal. The CG-5 gravimeter measures relative gravity using a base station loop which requires post-processing to obtain observed gravity values. Our post-processing of the FORGE gravity data resulted in 0.001 mGal of RMS error. The gravity survey conducted by the Utah Geological Survey (UGS) used high-precision GPS equipment that consistently achieved better than 0.10 m in elevation control (Figure 15, left panel, and Figure 16). Terrain corrections are computed by hand to within 0.001 mGal for each station. The gravity anomaly corrections are primarily dependent on elevation but are slightly affected by the reduction density value (assumed density of the average crustal density for the study area). The reduction density value plays a larger role in gravity modeling.

Intrinsic to the Earth's gravity field, the vertical gradient is much larger than the horizontal gradient. The vertical gradient, for example, can be approximated with the Free Air anomaly equal to 0.3086 mGal/m (formulation in Hinze et al., 2005). The horizontal gradient in the FORGE study area is calculated between 2 and 5 µGals/m, which is two orders of magnitude smaller than the vertical gradient. Because of this, the major factor affecting the accuracy of gravity measurements is elevation control. High-confidence elevation control (more difficult to achieve) is more important than horizontal control when making gravity measurements.

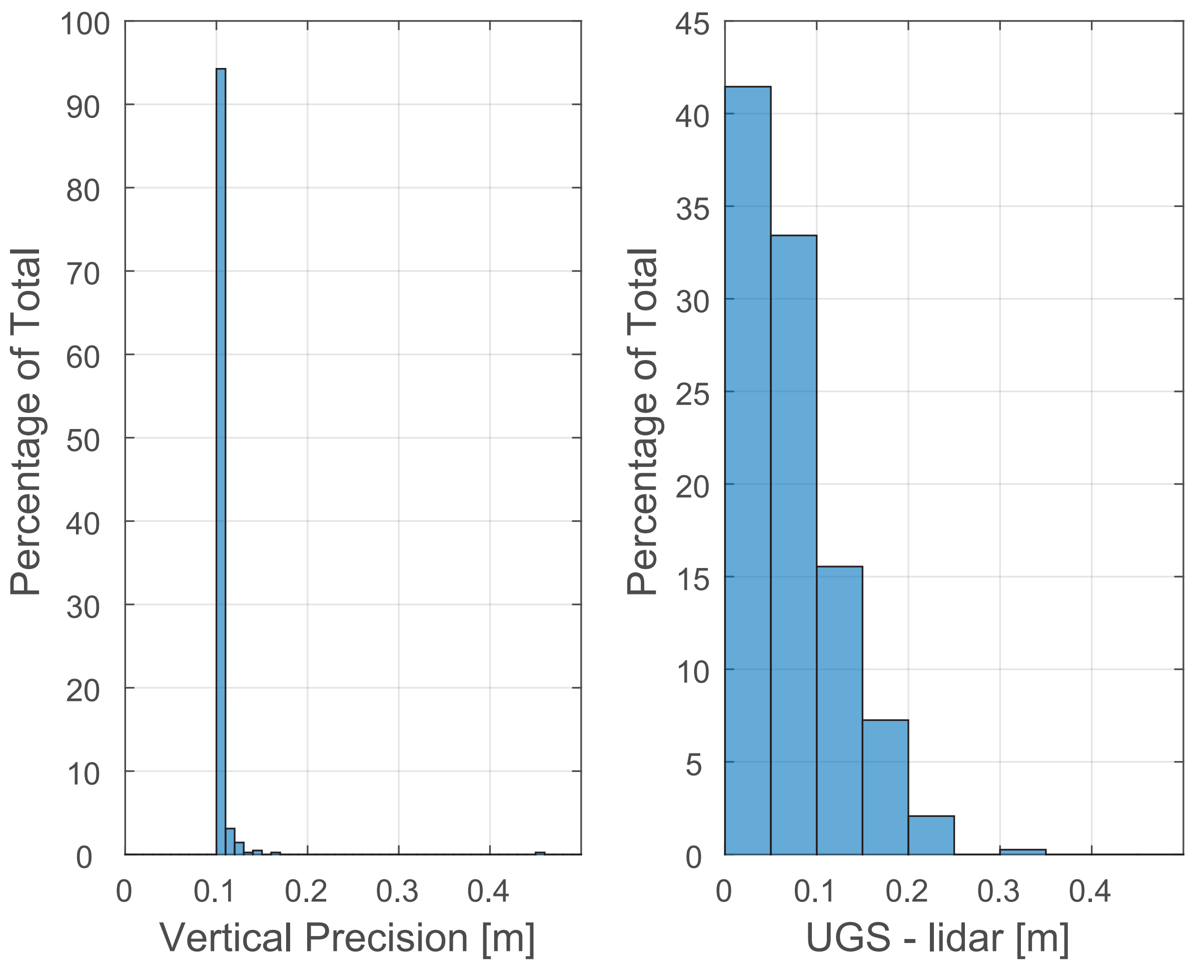

Figure 15. *Histograms of UGS gravity station elevation data. The left panel shows the vertical precision of UGS-acquired data. Vertical precision is 0.1 m or better at 394 of 418 positions (94.26%). The right panel shows differences between a subset of overlapping UGS-acquired elevation data and the lidar data collected for FORGE, where 291 of 388 UGS-acquired elevation values (75%) are within 0.10 m of the FORGE lidar values.*

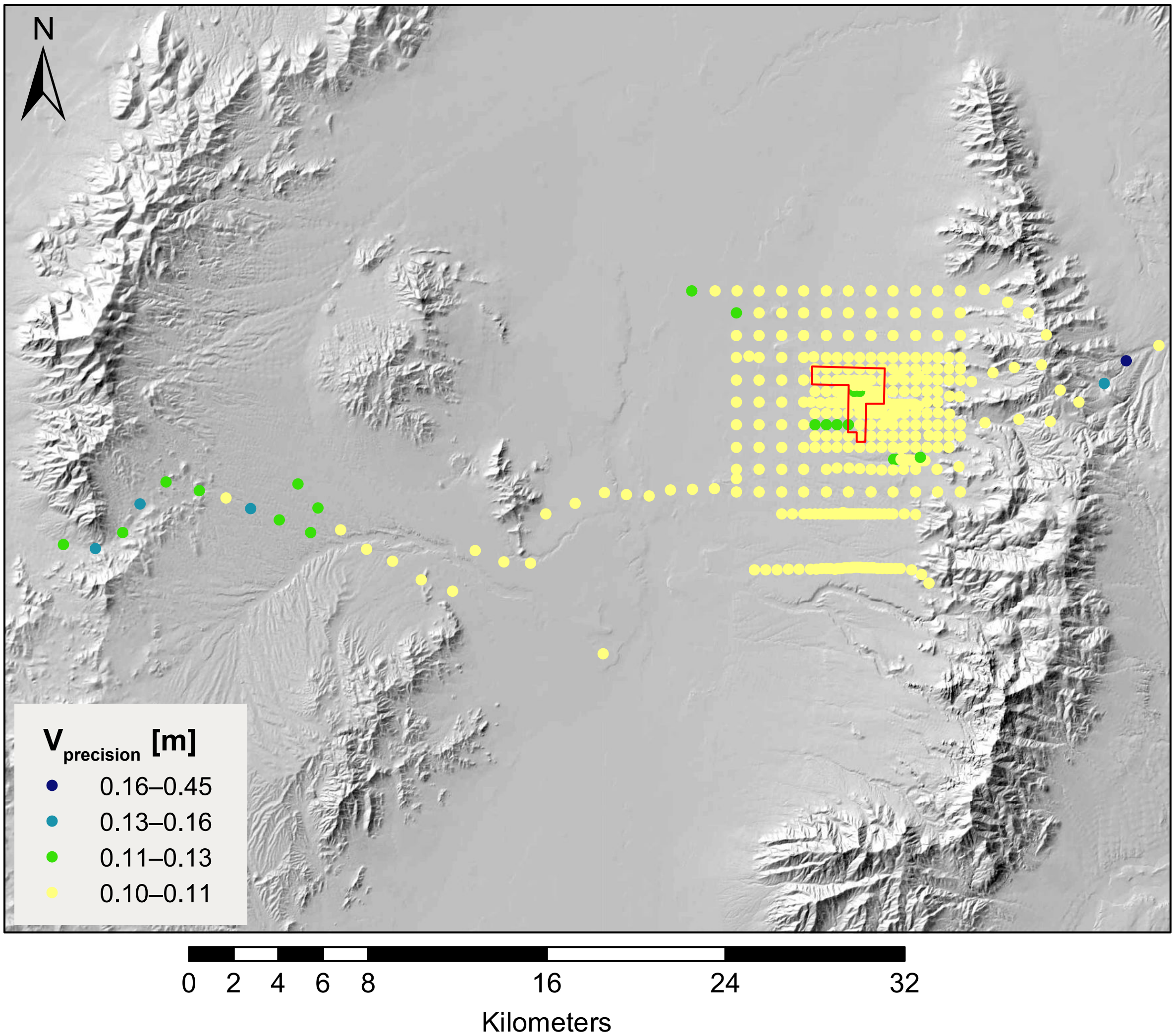

Figure 16. *Map of new FORGE gravity stations indicating vertical precision from post-processed GPS data. FORGE site outlined in red.*

For an elevation quality check, we compared UGS gravity station data to that of the lidar data acquired for FORGE (Knudsen et al., 2018), which reports vertical accuracy of 0.05 m. For the UGS gravity stations that overlap with lidar coverage, we report that 291 of 388 (75%) station elevations are within 0.10 m of the FORGE lidar values (Figure 17, right panel). The minor differences between the lidar and UGS stations are not unexpected, since the reported vertical precision of the stations is typically 0.10 m or better.

The legacy gravity data (PACES) does not have elevation control values reported in its metadata, so we compared their elevations with FORGE lidar and NED10m (if outside of the lidar coverage) to evaluate their accuracy. NED10m data is from a composite digital elevation model reported to have 3-m vertical accuracy from the U.S. Geologic Survey. A total of 3389 PACES gravity stations were used in this study, and 691 PACES stations are within the coverage area of the FORGE lidar. Figure 17 shows that 553 of 691 station elevations (80%) are within 3 m of the FORGE lidar values and 2767 of 3389 station elevations (81.4%) are within 3 m of the NED10m values (see also Figure 18). Most of the legacy gravity surveys were done prior to modern GPS equipment and survey techniques. Therefore, a 3-m vertical accuracy is assigned to the PACES data which is consistent with the vertical accuracy of older topographic maps.

Carefully considering the vertical uncertainties of each of the gravity data sets, we can propagate these uncertainties into the CBGA value and, subsequently, their estimated impact on gravity models. To do this, we computed the significant components directly related to the data elevation uncertainties. We focused on the Free Air anomaly, noted earlier, and the Bouguer Slab correction which is the approximation of the gravity effect from rock between a station and sea level using a 1D, horizontal plate. Initial 2D models of gravity transects can use a thickness-weighted mean of all the geologic layers in a basin to estimate

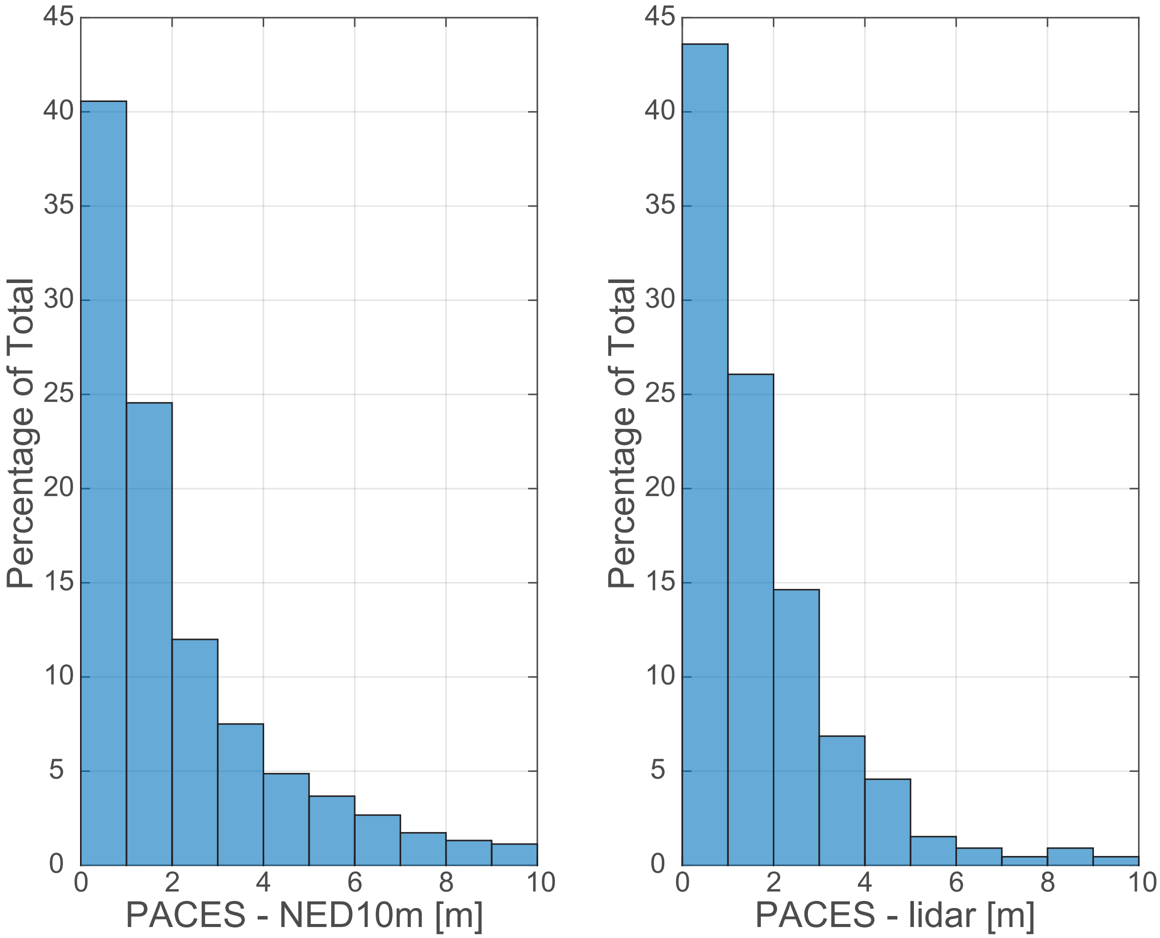

Figure 17. *Histogram of PACES gravity station elevation data comparisons. The left panel shows the differences between all PACES data and the NED10m data, where 2767 of 3389 station elevations (81.4%) are within 3 m of the NED10m values. The right panel shows the differences between a subset of overlapping PACES and lidar data collected for FORGE, where 553 of 691 station elevations (80%) are within 3 m of the FORGE lidar values.*

the depth-to-basement. For the FORGE study area, this density value is at a contrast of 0.3 g/cm^3 or the equivalent density of 2.37 g/cm^3. For the UGS gravity data, 0.1 m of vertical uncertainty equates to 0.031 mGal in the Free Air correction and 0.011 mGal in the Bouguer Slab correction, for a total of 0.042 mGal uncertainty and 3.5 m of difference in slab thickness. In the PACES data, 3 m of vertical uncertainty equates to 0.926 mGal in the Free Air correction and 0.336 mGal in the Bouguer Slab correction, for a total of 1.262 mGal uncertainty and 105 m of difference in slab thickness.

2D gravity models are most accurate when they can be tied to local density information. For the FORGE gravity models, density data from well logs, well cuttings, rock outcrops and other geologic information sources were utilized where most applicable. Gravity sections that run close to actual gravity data had the highest confidence (all other factors being the same), especially sections making use of the new FORGE gravity data. Where UGS and PACES data overlap, UGS data was given preference because it has higher confidence. For areas without modern gravity data, the confidence is lower. If the station coverage is of high spatial density, local data can be compared to determine consistency in observed gravity and elevation, and its confidence can be carefully evaluated.

It should be noted that gravity field sources decrease with an inverse-square relationship ($1/x^2$) to distance. Therefore, sources far from the observation point (larger x value) will have very small effects relative to sources closer to the observation point (smaller x values). Regarding basement structure, the implication is that it is unlikely gravity will resolve the same small-scale features at great depth compared to when they are near the surface. This results in deeper structures having the tendency to appear smooth compared to shallow features that show more detail. Furthermore, 2D gravity modeling assists in defining basin geometry, providing a better understanding of simple structure for areas where the gravity field appears to be two-dimensional. In cases where there are 3D structures, 2D gravity models will not delineate these structures with high confidence and 3D modeling will be required to further investigate these 3D features.

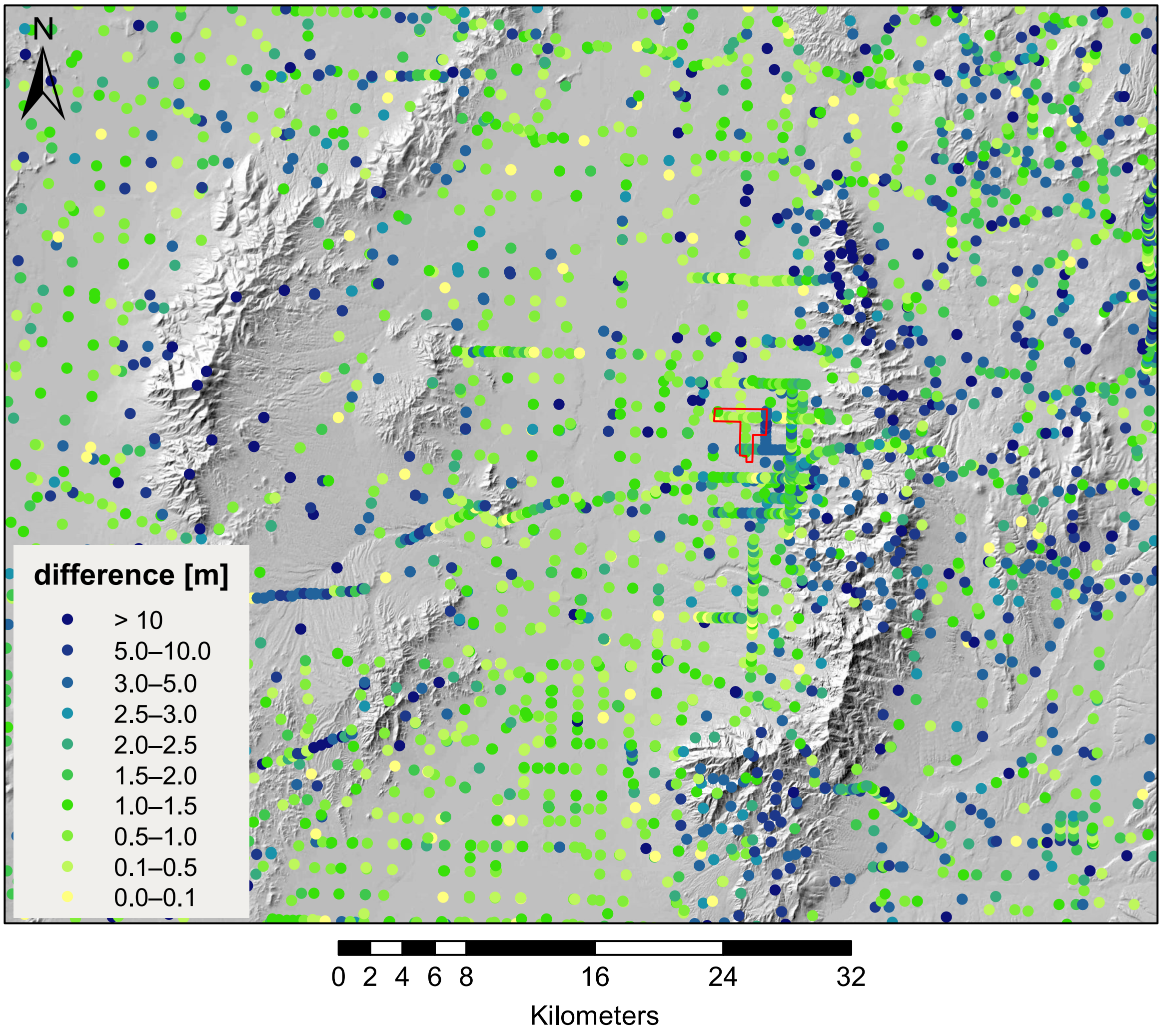

Figure 18. *Map of elevation differences between PACES station data and combined NED10m and lidar. FORGE site outlined in red.*

SUMMARY

Resistivity models from TEM sounding data better define features in the shallow subsurface near the FORGE site. A transect through the FORGE site delineates the depth to the groundwater table and does not indicate any subsurface structures are present. South of the FORGE site, a transect crosses the OMF, where a distinct resistivity contrast shows conductive material to the east of the fault that is interpreted to be primarily an effect of geothermal fluids that are prevented from flowing to the west by the fault. Resistivity along the Ranch Canyon Road transect is relatively higher compared to transects to the north, which is likely due to more resistive matrix material. The groundwater table is clearly delineated and no features consistent with a graben structure or fault are present. TEM data quality is good for nearly all stations and DOI values average 300 m. At this scale, uncertainty in depth of detected features is on the order of 5–10 m and model RMS values are typically less than 1.

Gravity surveys have better defined the basement geometry of the FORGE study area by augmenting legacy data with new, high-precision measurements using a dynamic grid layout centered on the FORGE site. 2D gravity models indicate that the deepest part of the basin, approximately 4.8 km in depth, is located on the west side of the valley, 12 km from the edge of the FORGE site boundary. Basin geometry from the 2D gravity modeling shows a steeply dipping interface on the east side of Milford Valley north of the FORGE site. The sediment-basement interface below the FORGE site appears to be moderately dipping (about 25˚) to the west, which is consistent with interpretations of the 2D and 3D seismic sections. Adjacent to the FORGE site, unresolved 3D structure is suggested by the horizontal gravity gradient field. From the seismic section interpretations, this structure appears to be a paleo valley in the granite surface. This feature is located at the margin of the grid where station coverage is less dense. New data collection (improved coverage), 3D modeling, and joint interpretations with 3D seismic will be required to better image this feature.

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